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New Sensors to Track Head Acceleration during Possible Injurious Events

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711th Human Performance Wing
Human Effectiveness Directorate
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New Sensors to Track Head Acceleration during Possible Injurious Events

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ABSTRACT

Instrumented earplugs were first introduced in 2000 by the Air Force Research Lab (AFRL) as a means of measuring head accelerations in race car drivers after it was shown that instrumented helmets slipped on the head during impact events. A version of these earplugs was adopted by the Indy Racing League and Championship Auto Race Teams (CART) in 2003. In 2006, Begeman, Melvin, Troxel and Mellor reported that signals from earplugs mounted in cadavers showed a phase shift at 50 and 100 Hz vibration indicating less than perfect coupling with the head. This led to the development of a new miniature tri-axial accelerometer that is small enough to be placed in the ear canal portion of communication earplugs (earpieces) thereby improving the coupling and thus the reliability of the recordings from drivers undergoing multi-axial crash events.

The first part of the effort involved developing design specifications for the next generation earplugs. These came from Andrew Mellor at the Fédération Internationale de l'Automobile (FIA) Safety Center who developed these specifications with a view toward using the new earplugs in the F1 race series. Endevco/Meggitt proposed to develop this mini-triax and secured congressional funding to support the development of a manufacturing process to reliably produce the new sensor. The AFRL team collaborated with Endevco/Meggitt to build the new sensors and provide the validation testing and comparison with the current operational sensors. The new 7273GT sensors were mounted in molded earplugs and subjected to impacts as high as 300g with very short durations in multiple axes. The earplugs were mounted in artificial ears which were mounted on rigid blocks. The sensors showed good correlation with reference sensors and demonstrated improved coupling to the head over the current generation of earplug accelerometers.

INTRODUCTION

Racecar drivers sometimes sustain a concussion during a crash. In 1998 when this research effort started there were no data recorded during such events that would relate head acceleration to the type and extent of injury. The Biomechanics Branch, of the Air Force Research Laboratory (AFRL/RHPA) has researched human response to acceleration for more than fifty years using volunteer subjects and instrumented manikins. (See: https://biodyn1.wpafb.af.mil) Instrumented earplugs were introduced by RHPA in 2000 as a means of measuring head accelerations in race car drivers after it was shown by RHPA that instrumented helmets slipped on the head during impact events. (Hill, Knox and Crockett, 2000). The initial earplugs used Endevco 7269 triaxial accelerometers developed especially for this effort by Endevco for AFRL. While the 7269 accelerometers worked, they were more expensive than the race teams or sponsors were willing to pay, and the 7269s required a preamplifier to interface with the Delphi ADR2 crash recorder.

At an informal group working meeting after the annual meeting of the International Council of Motorsport Sciences (ICMS) it was decided that Delphi would reengineer the earplugs using less expensive sensors from its airbag development project, and that RHPA would test the new earplugs on its Horizontal Impact Accelerator with human volunteer subjects. The selected sensors were less expensive and included an amplifier that facilitated connection to the ADR2. RHPA staff met with the Delphi engineers, under a Cooperative Research and Development Agreement, to share lessons learned, and some earplug units from the previous development. After testing during 2002, this new version of the earplugs was adopted by the Indy Racing League and Championship Auto Race Teams (CART) in 2003. Results from RHPA were reported at SAE Motorsports conferences in 2000, 2002 and 2004

as well as ICMS and FIA meetings over the same period. In 2006 Begeman, Melvin, Troxel and Mellor (Begeman et.al. 2006) reported that signals from earplugs mounted in cadaver heads showed a phase shift at 50 and 100 Hz vibration indicating less than perfect coupling with the head. A possible solution to this problem was presented by Andy Mellor (FIA Safety Institute) during the SAE Motorsports meeting. The idea was to develop a smaller sensor that could be placed deep in the ear canal portion of the earplug to help couple it to the skull. During the past year, two new miniature tri-axial accelerometers have been developed that are small enough to be placed in the ear canal portion of communication earplugs (earpieces) as a way of improving the coupling and thus the reliability of the recordings from drivers undergoing multi-axial crash or blast events. The focus of this paper is to report on the initial laboratory evaluation of these two new sensors and on their use in earplugs.

Previous studies have shown that the Delphi Sensor agreed well under linear impact conditions using the RHPA Vertical Impact Device (VID) (Knox, 2002, 2003). The following plot compares the response of the Delphi Sensor in the earplug taped to the VID carriage, with a reference sensor. The Delphi sensor was mounted in an earplug and then inserted in a rubber ear attached to a manikin head. This test setup resulted in a number of oscillations after impact. To assess the source of the oscillations, one sensor/ear combination was mounted on the manikin head while another sensor/ear combination was mounted on an aluminum block attached to the carriage of the VID. As shown in Figures 1, 2 & 3, most of the oscillations are due to movement of the “skin” of the manikin head (shown by blue line on plot) while the remaining oscillations are due to the earplug/ear combination (shown by yellow line on plot). It was these observations and the recordings from race drivers that prompted Begeman et.al. to conduct the study with cadavers in which the need for better coupling between the sensors and the head was identified.

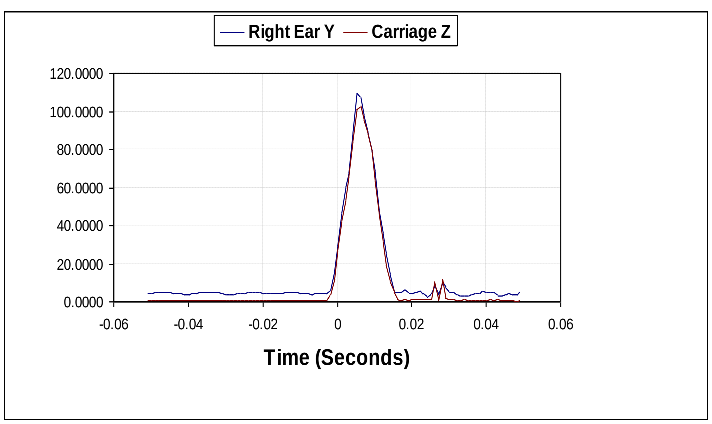

Figure 1. Delphi Sensor Response to 100 +Gy Impact (same direction as Carriage +Gz) from Knox et.al. 2004

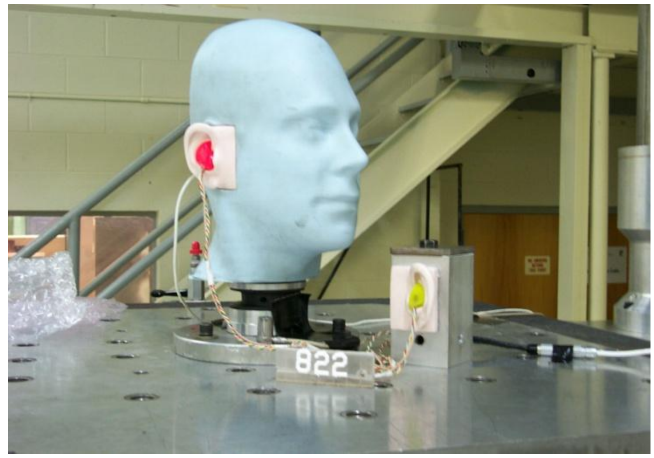

Figure 2. Test Vibration Source (skin or ear or both)

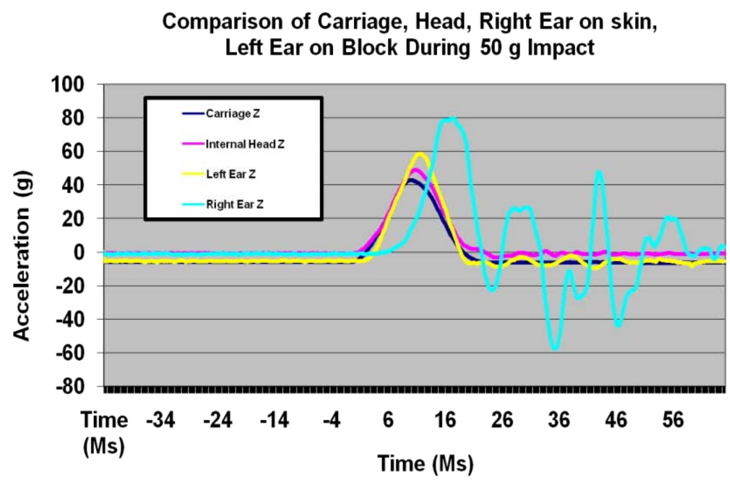

Figure 3. Plot of data from experiment depicted in Figure 2

METHODS

Samples of a new mini triax sensor, model 7273GT, were provided to AFRL/RHPA under a contract to develop the manufacturing process for this new sensor. The specifications were +/- 300 g, 0 – 1000 Hz with a mounted resonant frequency of 17,000 Hz. Another new sensor, model 73M1 with specs of +/- 6000 g, 0 – 20,000 Hz and a resonant frequency of 180K Hz was tested in parallel. A reference sensor, Endevco 7264C-2000 with specs of +/- 2000 g 0 – 2000 Hz (+/- 2% max) or 0 -5000 Hz (+/- 5% max) and mounted resonant frequency of 26K Hz.. All sensors were undamped so as to prevent phase shift.

Other sensors that were tested included the Delphi (Analog Devices 193) sensors used in current IRL Earplugs (0 –250 G and resonant frequency of 24K Hz). The sensor has a built-in amplifier with 2-pole Bessel filter (-3db at 400 Hz). In the earplugs three of the sensors are mounted to measure x, y, z accelerations by

being glued on an L-shaped bracket. See Figure 4 below.

Another sensor that was used was the Endevco 7269 which was the original sensor built for Race Driver earplugs (+/- 500 G, frequency response 0 to 3000 Hz with a mounted resonance frequency of 17K Hz).

A Model 7273GT is shown next to the IRL type earplugs in Figure 4. It is small enough to fit in the ear canal with no problem.

Figure 4. Indy Racing League type earplugs made by Sensaphonics (three Delphi AD 193 linear sensors)

Figure 5. The Endevco 73M1 tri-axial accelerometer

The Endevco 73M1 tri-axial accelerometer has a +/- 6K G range and resonant frequency of 180K Hz. The sensor was made for AFRL for testing at the University of Virginia in a study led by Dr. Bass. It is small enough to fit in the ear canal though not as small and light as the 7273GT.

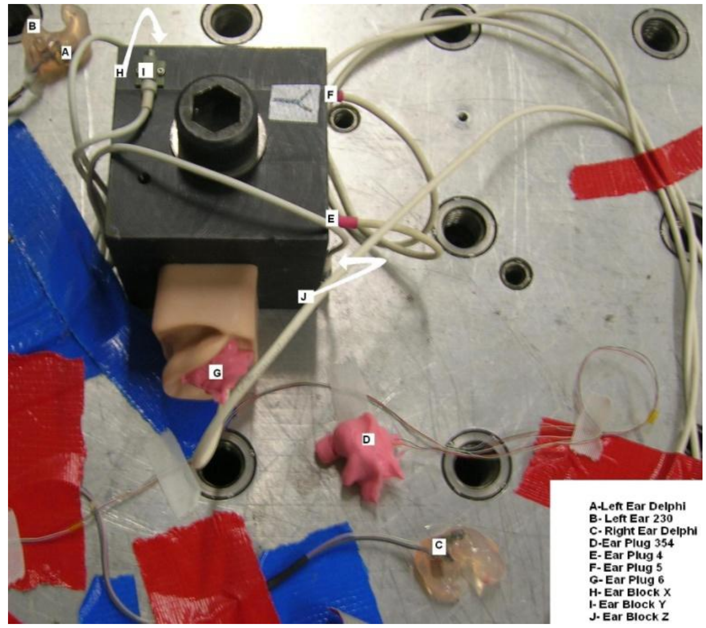

Figure 6. Impact Accelerator Test Configuration on the AFRL VID

The test configuration as shown above has the following accelerometers as labeled in Figure 6. (Endevco 7264C) on the Delrin block bolted to the carriage of the VID plus sensors mounted in a rubber ear and in earplugs held down to the carriage by tape (not shown).

A – Delphi AD 193 in tri-axial array in clear left earplug configuration as shown in Figure 4,
B – Endevco 7273GT # 230 mounted in the same earplug as A
C – Delphi AD 193 in right earplug configuration as shown in Figure 4
D – Endevco 7273GT molded in ear canal portion of an ear mold
E and F - Endevco 73M1 triax mounted on Delrin block
G- Endevco 73M1 located in ear canal portion of ear mold inserted in rubber ear and mounted on Delrin block
H, I & J - Endevco 7264C reference sensors screwed to Delrin block which is bolted to the VID carriage.

One 7264C reference sensor was screwed to the carriage of the VID, and is not shown.

The Vertical Impact Device (VID is shown with the carriage raised above the base in Figure 7. The VID is capable of producing impacts of a minimum duration of 1.6 ms and up to a maximum of 1000 g. The pulse characteristics are controlled by the drop height and the properties of the bumper materials such as elastomers, felt and mechanical shock absorbers attached to both the carriage and the impact base. Rubber bumpers in this picture were replaced by stiffer plastic bumpers and a layer of felt to obtain the desired pulse.

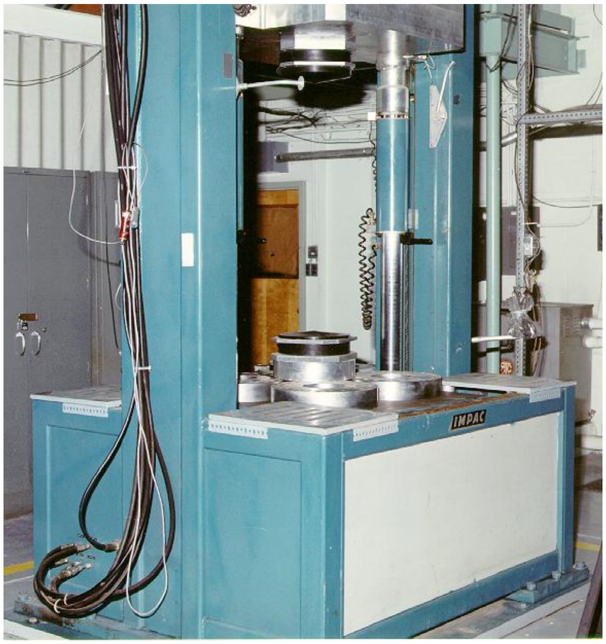

Figure 7. Monterey IMPAC Vertical Impact Device (VID)

VIBRATION TABLE

In addition to the tests on the VID, sensors were subjected to vibrations on hydraulic, pneumatic or electro-dynamic shakers to assess the introduction of phase shifts in the output of the sensors under various mounting configurations.

ELECTRONIC DATA

Data was acquired using either a DTS Pro or a DTS G5 data system with various sample rates and filter settings. DTS software was used to control the data collection and initial inspection. Analyze Test, software written at AFRL/RHPA, was used to filter, analyze and plot the results.

Data collected with the DTS Pro 8 channel DAS used a 100k Hz sample rate with no filter. This was done to look at system oscillations and to collect data for spectral analysis to facilitate later filtering. The large mass of the VID rings when it hits the even larger reaction mass. At high acceleration levels this ringing can set up oscillations at the resonance frequency (26K Hz) in the undammed reference sensor (7264C-2000). Proper filtering can remove these extraneous signals.

The DTS G5 32 channel DAS has a 12,500 Hz sample rate per channel, with a hardware anti-aliasing 4K input filter or 10,000 Hz with software 3K 8 pole Butterworth anti-aliasing filters. The G5 has 32 channels so many sensors could be recorded simultaneously.

The test data was saved in XL spreadsheets for later processing.

RESULTS

Prior to conducting tests on the new, miniature accelerometers, RHPA securely mounted a 3-axis sensor module from an IRL type earplug on a calibration shaker table. Plots of the output at two frequencies are shown in Figure 8 below.

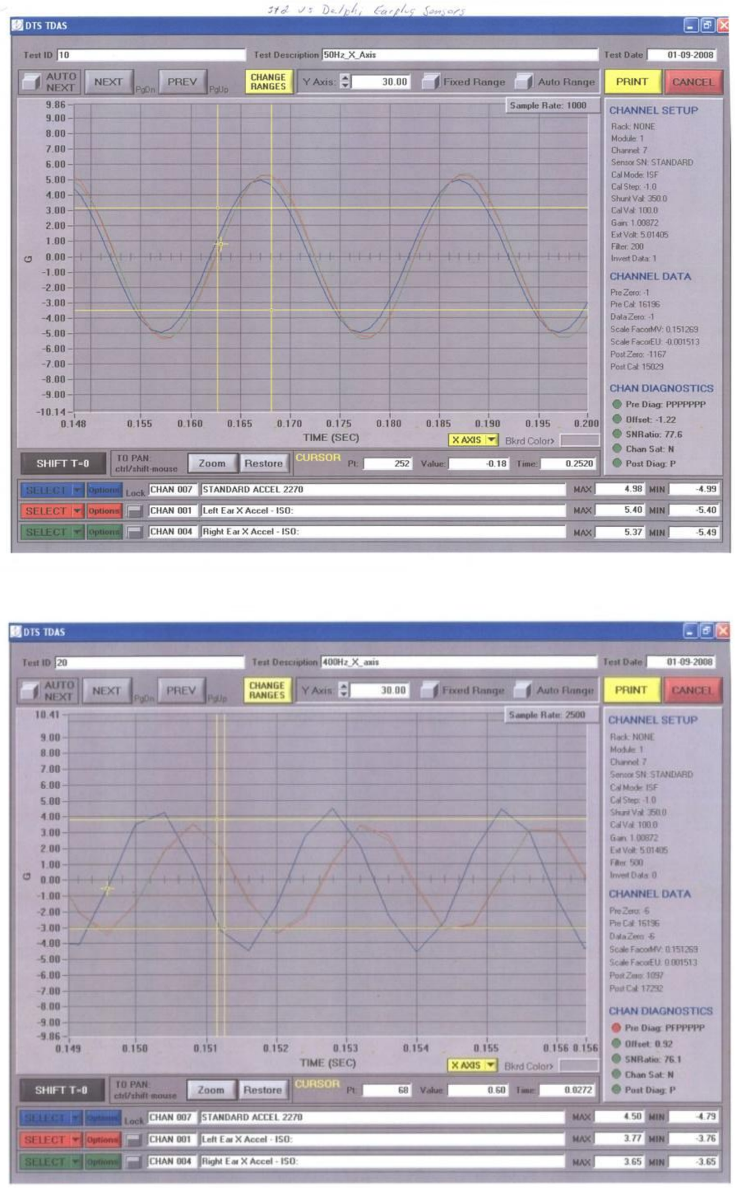

Figure 8. Output of Standard Reference Sensor (2270) compared to Delphi sensor

The frequencies ranged from 50Hz (top plot) to 400Hz (bottom plot). Notice the phase shift from 50Hz to 400Hz. Changes in gain and phase as a function of frequency can be seen in the summary plot below for the Delphi sensor.

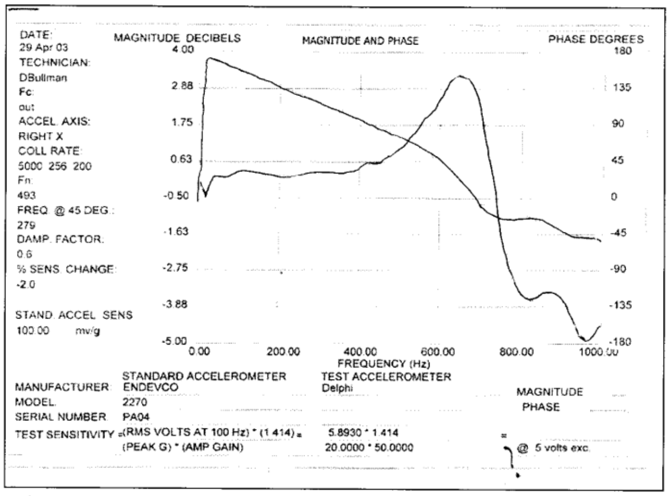

Figure 9. Magnitude and Phase as a function of frequency for the Delphi Sensors.

These phase shifts appear to be the result of the filter in the Delphi sensor (AD193). Similar tests conducted with the new 7273GT mini-triax which is unfiltered, showed an essentially flat response (+/- 1.9%, 20 – 2K Hz).

The 7273GT is small enough (1.5 x 1.8 x 2.0 mm) to be placed in the ear canal portion of an earplug containing the Delphi sensor package. This combined package was tested under linear G conditions. During the tests reported here, the earplug was 1) firmly attached to the Delrin Block bolted to the carriage of the VID or 2) placed in an earplug containing the Delphi sensor and either inserted in a rubber ear attached to the VID sequentially in all three orientations or taped directly to the top of the VID carriage (Refer to Figure 6).

The Endevco models 73M1 (experimental high G sensor) and 7273 (mini-triax sensors) were tested along with reference sensors (model 7264C-2000) according the following matrix: One hundred twenty nine (129) tests were completed using the following test matrix.

Because of the differences in range of the 7273GT (+/- 300 g) and 73M1 (+/- 6K g) sensors, not all exposures were used for both sensors to prevent damage. In the lower ranges, many sensors were used simultaneously while the 7273GT sensor was removed when the pulses were expected to be above 300g.

The impact level for each test was controlled by the drop height of the VID carriage (distance between plastic attenuators mounted on the bottom of the carriage and the impact isolation block at the base of the VID).

Orientation of the sensor is the sensor's internal orthogonal axis relative to the fixed axis of the VID carriage (carriage z-axis is always pointing up).

TEST MATRIX

Test Cell	Impact Level	# of Tests	Orientation	Approx. Height
A	50	3	X	1.75"
B	50	3	Y	1.75"
C	50	3	Z	1.75"
D	250	3	X	10"
E	250	3	Y	10"
F	250	3	Z	10"
G	500	10	X	27"
H	500	10	Y	27"
I	500	10	Z	27"
J	750	3	X	63"
K	750	3	Y	63"
L	750	3	Z	63"
M	1000	3	X	TBD
N	1000	3	Y	TBD
O	1000	3	Z	TBD
P	25	3	X	1"
Q	25	3	Y	1"
R	25	3	Z	1"
S	75	3	X	2.5"
T	75	3	Y	2.5"
U	75	3	Z	2.5"
V	150	3	X	5"
W	150	3	Y	5"
X	150	3	Z	5"
Y	225	3	X	8.5"
Z	225	3	Y	8.5"
AA	225	3	Z	8.5"

The following representative examples of recorded data are presented to illustrate the responses we recorded during one run.

- Plot of model 7273GT #354 Z accelerometer response to 1.75" drop 52.83 g
- Plot of model 7273GT #354 Y accelerometer response to 1.75" drop 7 g
- Plot of model 7273GT #354 X accelerometer response to 1.75" drop 7.71 g
- Power Spectrum 7273GT #354

The diagram with each plot below shows the sensor plotted and the direction of motion. Some care was taken to mount the sensor to the Delrin block but there may have been some relative motion between the

sensor and the block because we did not employ glue so as not to damage the sensor. Notice that the primary axis stimulated was “Z” because of orientation of the sensor to the direction of motion (z-axis of the VID carriage).

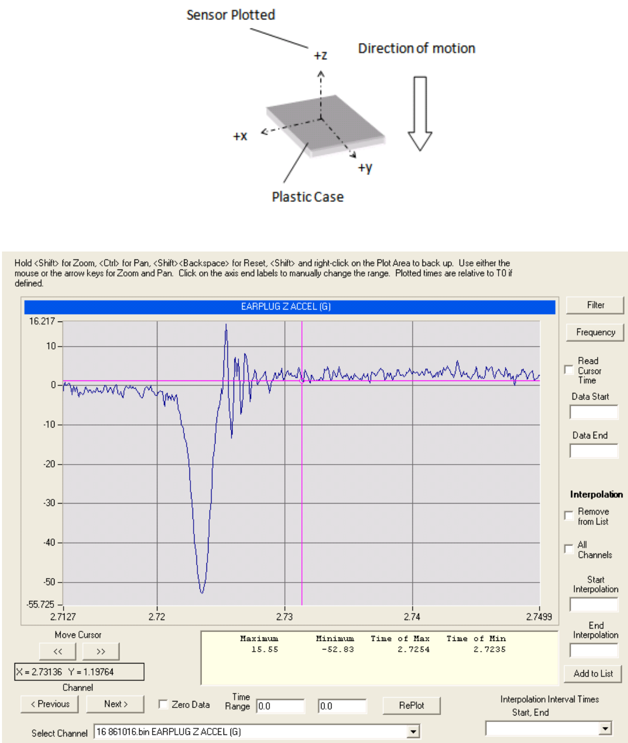

Figure 10. Plot of Model 7273GT Z-axis Accelerometer

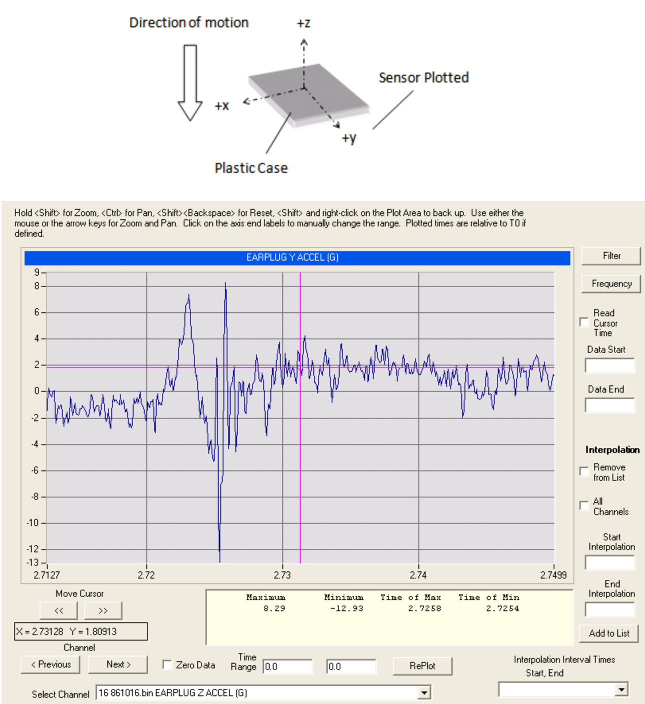

Figure 11. Plot of Model 7273GT Y-axis Accelerometer

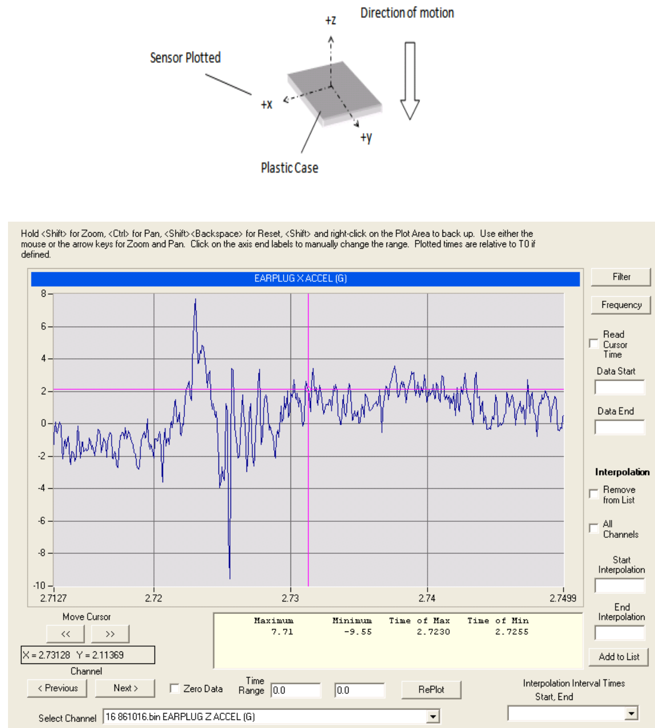

Figure 12. Plot of Model 7273GT X-axis Accelerometer

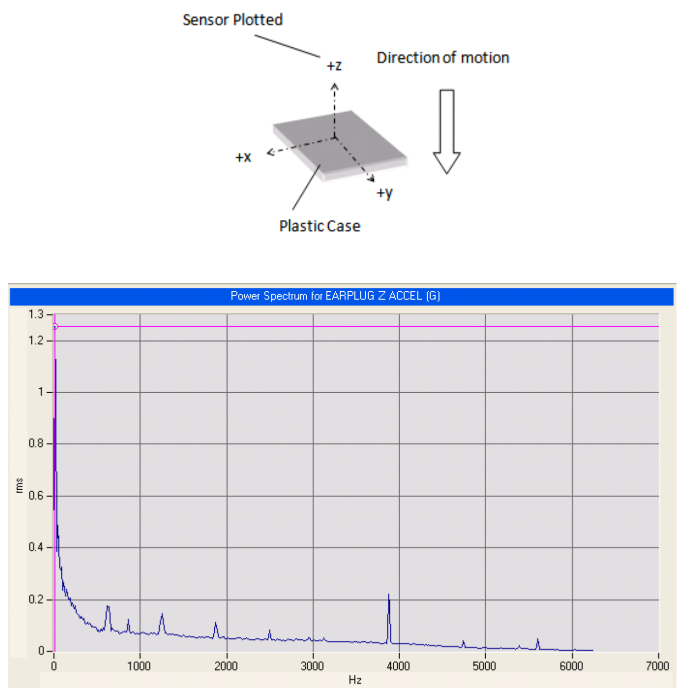

Figure 13. Power Spectrum Plots Used to Select Filter Frequencies

The software settings for the power spectrum analysis were the following: Welch Method, window length of 1000 points, overlap of 500 points, and FFT length of

1000 points. Notice that most of the information is well below 2000Hz. The few spikes may have been due to anomalous data points.

Test 861 Resultant Plots

The following data was selected to illustrate the affects of the pre and post test processing. The TDAS G5 filters at 4K on its own and is shown as the pre-processed data.. The post processing data is all filtered at SAE J211 Class 1000 filter of 1650Hz. Plots show acceleration in g vs. Sample # so 20 = 2.0 ms and 120 = 12 ms on a time scale.

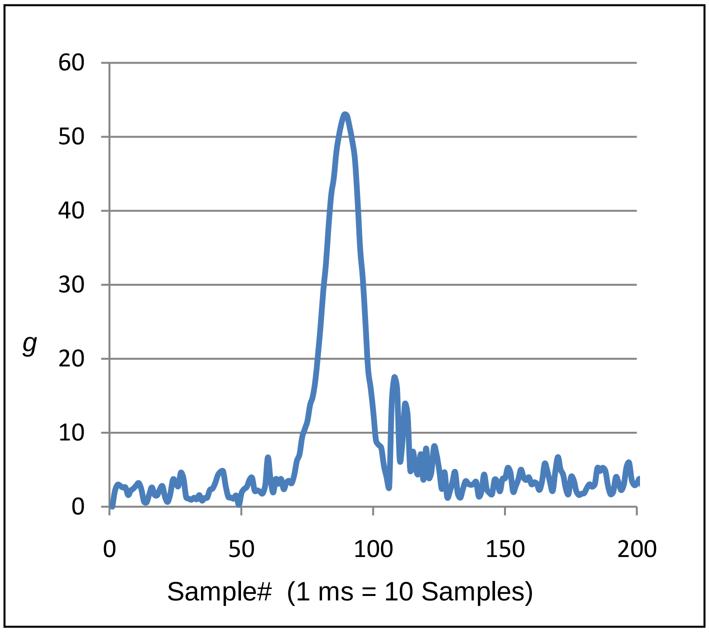

Figure 14. Pre-Processing Plot

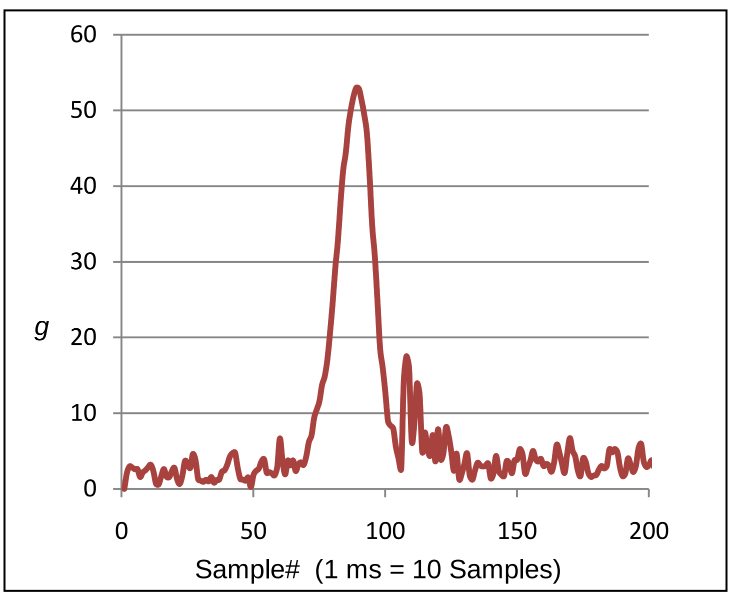

Figure 15. Post-Processing Plot

One purpose of this study was to compare the Delphi sensor's response in its normal place in the earplug with a 7273GT located in the ear canal portion of the same earplug. The results of this comparison follow. In these plots no extra filters have been employed beyond the 4K Hz filter built in to the DAS. In the first three plots the Delphi Earplug was subjected to drops of 1.75", 5.0" and 8.5" while the carriage reference sensor, the Delphi sensor and a 7273GT # 230 in the ear canal part of the Delphi earplug mounted in the rubber ear fastened to the Delrin block were recorded.

Sensors in the Delphi Earplug in Rubber Ear on Delrin Block

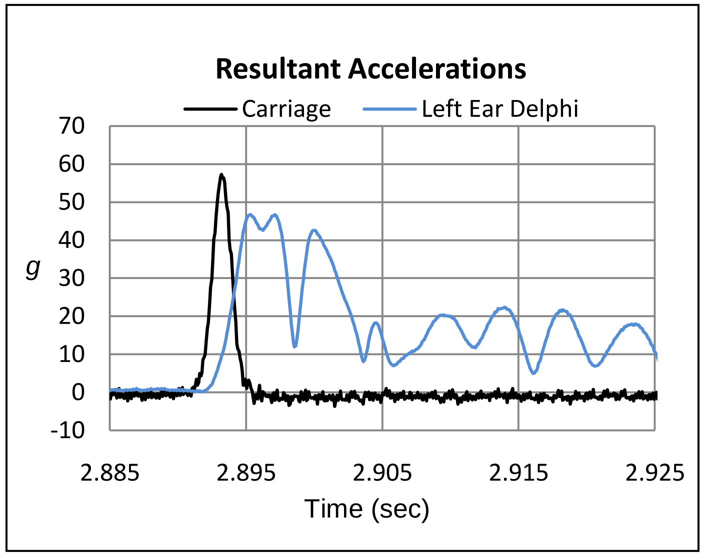

Figure 16. Plot of Test #932 with a 1.75' drop

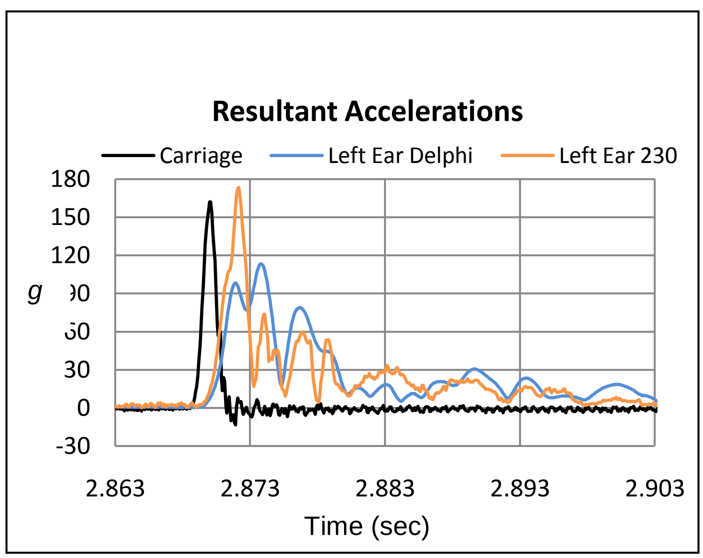

Figure 17. Plot of Test #939 with 5.0" drop

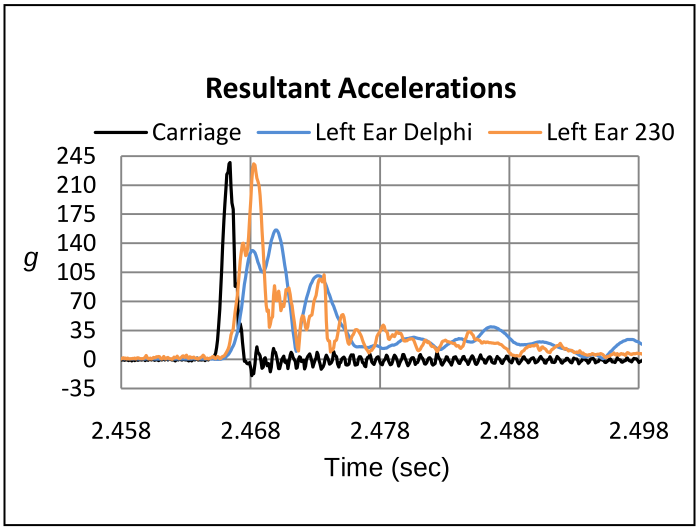

Figure 18. Plot of Test #942 with an 8.0” drop

In the second set of three plots, the Delphi earplug was taken out of the rubber ear and taped to the carriage so that the effect of the rubber ear would be apparent. All the Plots are acceleration (g) as a function of time (ms).

<u>Sensors in the Delphi Earplug Removed from the Rubber Ear and Taped to the VID Carriage</u>

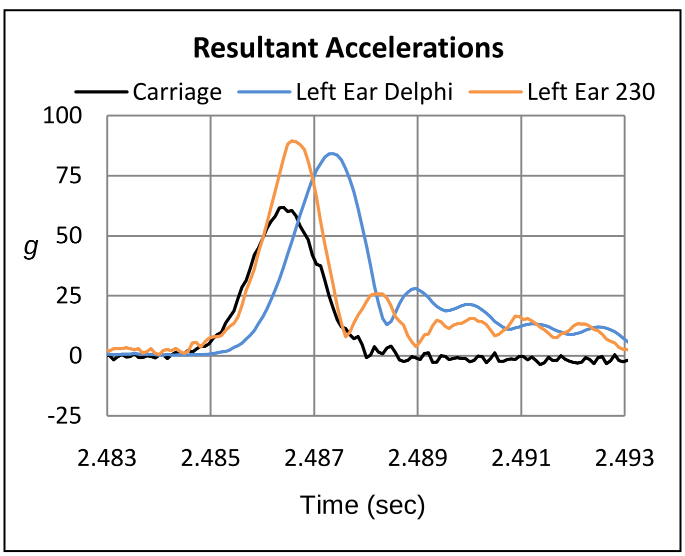

Figure 19. Plot of Test #956 with a 1.75” drop

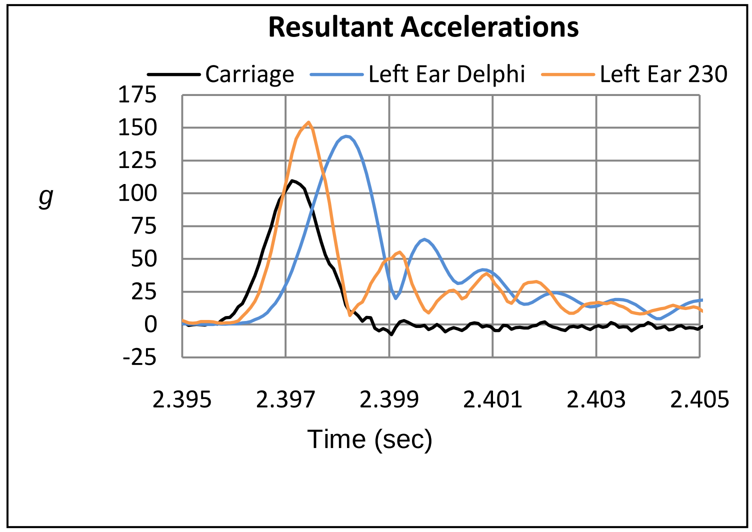

Figure 20. Plot of Test #957 with a 5.0 “ drop

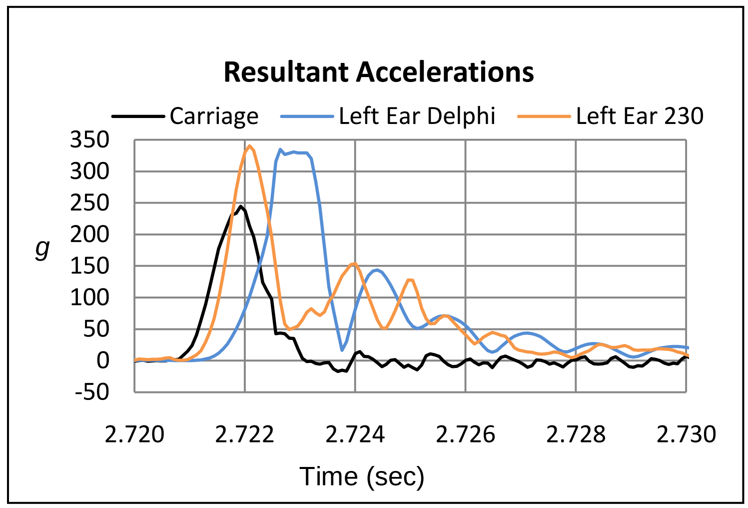

Figure 21. Plot of Test #958 with a 8.0” drop

Note that the time scale in the second group of three plots is 5x smaller than the first group of three (2ms per vertical line for tests 932, 939, 942 vs.10 ms per vertical line for tests 956, 957, 958). Notice also that the saturation of the Delphi sensor at above 300 g. its specified range is +/- 250 g.

We also calculated the percent error between the Block Accelerations and all the other sensors. The results are summarized in the tables in the Appendix because of their size. It should be noted that it was impossible to set the VID to give exactly the same impact each time so some of the variability was probably due to that in addition to the minor shifting of the sensors on repeated impacts. For each of the sensors, there is a stated uncertainty as a function of acceleration. The uncertainty for the 7273GT and the 73M1 sensors was +/- 1.9% for accelerations between 20 and 2000 g.

DISCUSSION

Approximately 129 tests were conducted of two new sensors designed for mounting in the ear canal of persons subjected to impact during crash, sporting events, or blast related events. The critical question to be answered during these tests was whether the new sensor placement (deeper in the ear canal portion of communication earplugs) can actually record the impact event more accurately than previous earplug configurations that are currently being used by IRL and Champ Car race series (now combined). It would appear that the new sensors work somewhat better but the tissue surrounding the ear canal must be factored in to the analysis.

These initial tests identified the occurrence of vibrations in the carriage of the VID test facility and in the sensor mounting block, and that at high impact levels, these vibrations can interfere with accurately reading the pulse of interest. By enhancing the Analyze Test software to conduct spectrum analysis and to properly filter the recorded data, it was possible to select filter properties that did not distort the pulse of interest while minimizing the effect of the carriage and mounting block vibrations.

In the results section above, a few examples of the power spectra and the filtered pulses were shown. Additional data accompanied by statistical analysis to document the reliability and error associated with the use of the new mini triax (7273GT), as mounted deeper in the ear canal, compared to the current Delphi sensor in the outer portion of the earplug, will be made available on the AFRL Biodynamic Data Network located on the web with special permission (contact authors).

CONCLUSION

These preliminary results have shown that a new mini triax that is small enough to fit in the canal portion of earplugs works well in recording impact events. A newer version with an amplifier has been delivered for testing. The next area for investigation is the task of optimizing the design of the earplug using materials to minimize the phase lag and oscillations that we have observed. The stiffer epoxy material used at UVA for the studies using the model 73M1 sensor with cadaver specimens showed some promise in this regard. There is still the problem of the thin layer of compressible tissue lining the ear canal that prevents the earplug from being completely coupled to the skull. A plan has been developed to address this issue by modeling the tissue and earplug material to allow the recorded earplug accelerations to be corrected back to estimated skull accelerations.

Preliminary efforts using this approach have been completed by calculating an average transfer function for 11 tests conducted with cadaver specimens at UVA.

The following figures show the average transfer function for the 11 tests.

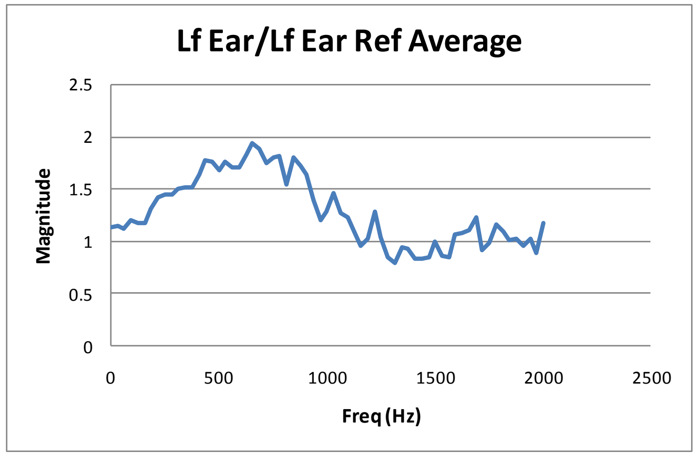

Figure 22. Plot of Average Transfer Function

As an example, deconvolution was used to compute the left earplug reference resultant acceleration (which was recorded from sensors fastened to the skull) from the measured left earplug resultant acceleration for tests 1_2 and 2_7 using the average transfer function shown above. The deconvolution was computed in the frequency domain by dividing the FFT of the left earplug resultant acceleration by the average transfer function and then computing the inverse FFT. The following two figures show the results. Dividing by the average transfer function reduces the magnitude of the signal. The transfer function frequency components above 2000 Hz were set to zero before the computation. For comparison, the measured signals were also filtered by computing the FFT and setting the frequency components above 2000 Hz to zero.

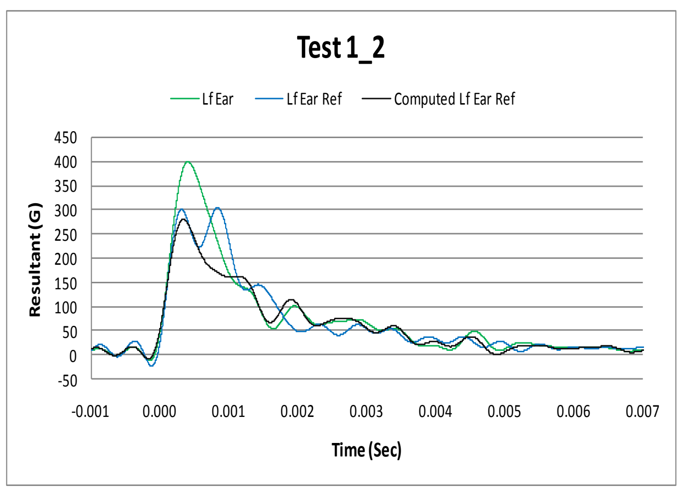

Figure 23. Plot of Computed Left Ear Acceleration Using Transfer Function for Cadaver Test 1-2

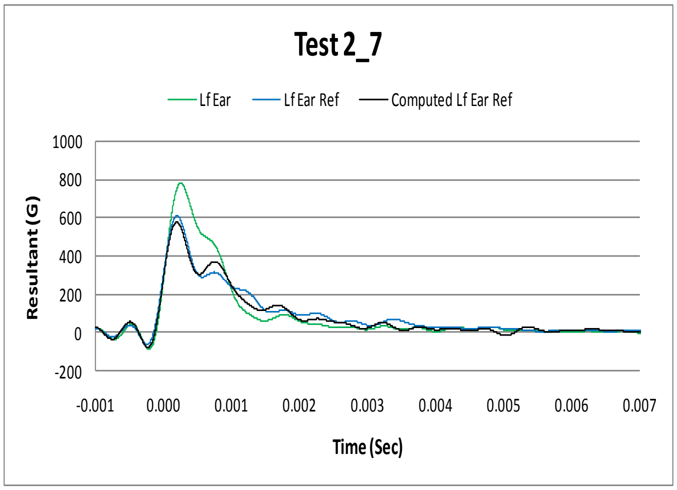

Figure 24. Plot of Computed Left Ear Acceleration Using Transfer Function for Cadaver Test 2-7

Notice that the transfer function for the cadaver series 1 test is less consistent than that for the cadaver series 2 test. The coupling observed for the second set of experiments was better than the first.

The fit we see in this example leads us to believe that through careful earplug design and application of modeling, it will be possible to obtain a sufficiently accurate estimate of skull (head) acceleration. This will be useful in designing better head protection and perhaps recommendation for further clinical evaluation for suspected head injury.

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APPENDIX: MEAN ACCELERATIONS AND % ERROR

Table of Average Acceleration (g) Values												
	Earplug (73M1)			***Carriage (7264C)***			***Block (7264C)***			***7273 GT***		
Height	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
1"	33.62	37.30	33.51	34.07	35.99	32.09	32.82	37.48	30.81	35.12	34.44	29.29
1.75"	57.55	62.36	58.62	57.24	61.04	56.68	56.18	62.71	54.30	58.07	58.94	53.67
2.5"	84.29	90.68	84.85	84.33	88.74	81.59	82.32	91.41	77.68	87.30	86.30	78.03
5"	150.83	160.71	154.69	151.637	158.55	148.9433	149.693	162.59	141.27	154.92	152.94	137.76
8.5"	228.79	245.24	237.99	231.42	239.52	233.35	231.49	242.56	221.18	232.34	234.57	212.18

Table of Average Percent Error (%) Values Relative to Block									
	Earplug (73M1)			*Carriage (7264C)*			*7273 GT*		
Height	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
1"	2.42	0.46	8.76	3.79	3.95	4.13	6.16	8.84	8.05
1.75"	2.45	1.85	7.95	1.89	2.66	4.40	3.25	6.47	4.10
2.5"	2.38	0.90	9.23	2.44	2.92	5.05	5.70	5.92	3.09
5"	1.04	1.15	9.49	1.31	2.47	5.43	3.40	6.31	2.54
8.5"	1.16	1.11	7.60	0.79	1.24	5.52	0.47	3.41	4.25
Average	**1.89**	**1.10**	**8.61**	**2.05**	**2.65**	**4.90**	**3.80**	**6.19**	**4.41**

**The block acceleration (7264C) values were used as the reference in calculating percent error*

****** *The large values for 73M1 "Z" may be due to the way the sensor is mounted – inserted into a hole ll to Z*